R&D Item

# 1. Development of new network architectures and protocols to realize robust and large-scale communication networks

## Progress until FY2024

### 1. Outline of the project

To realize a distributed quantum computer, it is essential not only to interconnect multiple quantum computers but also to build an integrated distributed quantum information processing environment that fully utilizes their combined processing capabilities, enabling unified execution of quantum applications. Achieving this requires three critical components: quantum computers themselves, communication interfaces, and quantum communication networks. Quantum communication networks, in particular, must exhibit efficiency, scalability, fault tolerance, and operability without performance degradation, even when handling large quantities of quantum data.

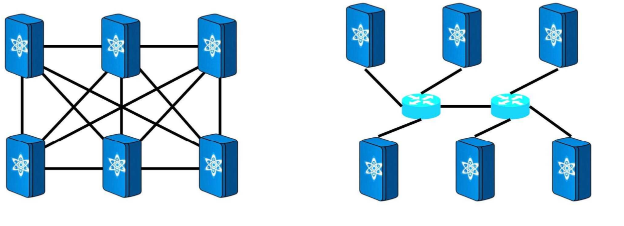



Fig. 1. Topic depends on network topology

Within the broader research and development program, this project provides foundational technologies necessary for practical distributed quantum computing. It aims to facilitate early realization of large-scale fault-tolerant quantum computation through networking quantum computers developed in other projects.

During this fiscal year, we began finalizing hardware metrics for quantum network demonstration and initiated implementation of classical aspects of quantum link protocols. We detailed inter-module interface specifications and advanced research toward implementation through simulations scaled up to 1000 nodes. Additionally, we clarified noise reduction technologies and dynamic network design guidelines, performing numerical analysis to compare performance across various purification protocols.

Specifically, this task aims to achieve optimal network design from architectural, protocol, and classical control perspectives. Through system design, testbed measurements, and corresponding network simulations, we elucidated the achievable system performance.

### 2. Outcome so far

This year, detailed evaluations of parameters such as error probabilities and photon loss rates were conducted to facilitate quantum network practical implementation, alongside the development of implementation models for quantum communication protocols and concrete error-handling strategies. Furthermore, space-division and time-division schemes for link-layer construction were explored, initiating the implementation of high-precision timing synchronization methods, including FPGA-based Time-to-Digital Converters and Dragonfly-type synchronization (TidyFly). Focusing on Q-Fly architecture as a network interface, the first physical demonstration experiments using optical switches were performed. Correspondingly, quantum network specifications were established, device control software (PnPQ) was developed, and repeater graph-state-based architectures were designed, including preliminary silicon photonics chip development.

Additionally, efforts were directed towards developing quantum state purification algorithms and addressing job scheduling challenges. Regarding noise reduction, the quantum relay system employing bosonic codes was evaluated and improved significantly by integrating quantum memory into cat codes. Dynamic structural analysis of latency-affected networks was conducted, proposing optimal configurations and protocol designs. Tools for purifying bipartite and multipartite states were also developed, assessing modular approaches to surface code implementation feasibility. Research aimed at simplifying quantum computer implementation via direct GHZ state generation commenced. Finally, foundational patterns for fault-tolerant communication combining cryogenic superconducting qubits and optical quantum communication were defined, establishing various essential performance indicators for realization.

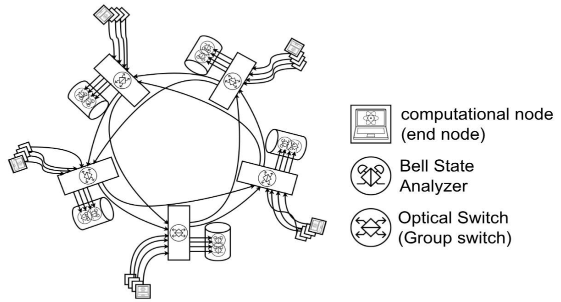



Fig. 2. Q-Fly Architecture

### 3. Future plans

Moving forward, intelligent network design combining theory, experimentation, and simulation will continue to be pursued to achieve efficient large-scale distributed quantum computers. Specifically, the goal is to integrate developments in quantum optical communication, quantum memory and relay technology, and distributed quantum applications using communication protocols and classical control techniques, operating testbeds as cohesive communication systems. Collaboration with other projects will also be emphasized to guide future developments from the perspective of large-scale distributed quantum computing architecture.

R&D Item

# 2. Quantum optical communication technology enabling precise control of quantum light

## Progress until FY2024

### 1. Outline of the project

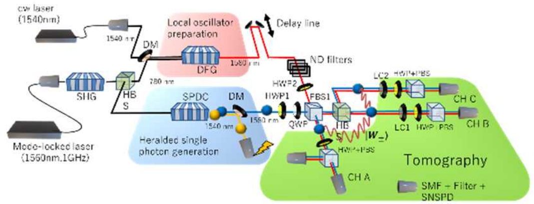
The aim of this project is to develop quantum optical communication technologies for the distributed quantum computing system where quantum computer nodes are connected via entangled photons.

Toward this goal, we employ two approaches: one is the two-photon interference approach and the other is the single-photon interference approach. The former is more matured and suitable for the near-term demonstration of the distributed quantum computing system. The latter is technically more challenging, but has potential advantages, such as loss-tolerance and suitability to wavelength-division-multiplexed quantum memories. The project includes developments of entangled photon sources, their evaluation techniques, phase locking between distant entangled photon sources, entanglement swapping, entanglement photon routing technologies. These technologies are directly contributing to develop the scalable and robust integrated quantum communication systems.

Fig. 1. Images of quantum optical experiments

### 2. Outcome so far

So far, we have successfully developed various underlying technologies for quantum optical communication, such as quantum frequency converters, entangled photon sources directly connecting the quantum memory wavelength and the telecom wavelength, frequency stabilization, optical phase locking and the loss-tolerant transmission techniques. Another important technology is the measurement and evaluation of the entangled photons. For bipartite entangled photon-pairs, the technique called the quantum state tomography is well developed and allows to reconstruct the precise quantum state of the entangled photons. However, for multipartite entangled photons, the quantum state tomography is not practical since it requires too many different measurements and too long time to complete it. Instead, we developed a simpler and time efficient new measurement technology, which captures the main feature of entanglement and allows to reconstruct the quantum state with reasonable accuracy. The idea was experimentally demonstrated for tripartite entangled photons. Figure 2 shows our experimental setup and result. The blue bars of the latter are the evidence that the three modes are quantum mechanically correlated, i.e. entangled.



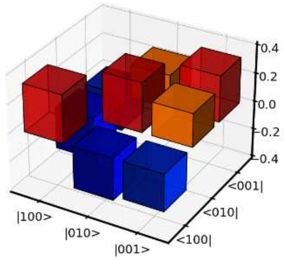



Fig. 2. Experimental setup (top) and the reconstructed tripartite quantum state (density matrix) (left).

### 3. Future plans

Our developed technologies are ready to be integrated to a prototype of the integrated quantum communication system. This prototype demonstration will be done by collaboration of all R&D items of the project.

Goal6 Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.

Scalable and Robust Integrated Quantum Communication System

Here begins our new MIRAI
MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

R&D Item

# 3. Quantum memory and quantum transducer for repeating and converting quantum signals

## Progress until FY2024

### 1. Outline of the project

In this project, we focus on the transduction between optical and microwave signals —and material quantum systems, aiming for the realization of quantum repeaters.

The technologies under development include quantum memory systems that interface with visible photons, such as rare-earth-doped material like Pr:YSO and rubidium atoms; quantum mechanical memories that couple to microwave fields; and enabling technologies such as frequency stabilization and quantum transducers that link quantum memories with optical signals. These efforts aim to establish entanglement between distant quantum memories and to advance quantum repeater technology, ultimately enabling the integration of superconducting quantum computers with long-distance quantum communication networks.

### 2. Outcome so far

**Development of Multiplexed Quantum Memories for Quantum Repeater Networks**

We have generated multiple quantum memory channels within the absorption spectrum of a Pr:YSO crystal. As shown in the figure, more than 30 memory channels have been successfully generated.

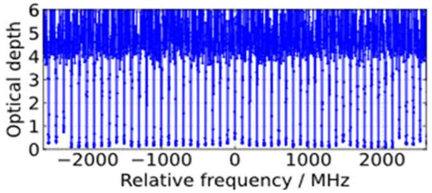



Fig. 1. Over 30 Memory Regions Created on Pr:YSO

**Development of stabilization techniques for light sources used in a quantum memory**

Frequency stabilization techniques have been developed for the light sources used in quantum memory experiments. In this year, we performed laser frequency stabilization for the laser source used to transfer the entangled photons. The frequency variation of the laser source used to transfer the entangled photons was suppressed to less than 1 kHz. We also developed an optical frequency comb with high reliability. We have realized the phase lock of the carrier-envelope offset frequency of the developed comb.

**Research on Enhancing the Reliability of Entangled Photon Generation via Spin Waves**

We constructed a magneto-optical trap (MOT) for capturing rubidium atoms and performed initialization of the atomic internal states for quantum memory operations. An optical cavity with low-loss mirrors was built, and its characteristics, such as finesse, were evaluated. In addition, we stabilized the laser sources used for cavity locking, quantum memory write-in, and read-out operations. We also prepared laser systems for generating a one-dimensional optical lattice to trap atoms inside the cavity.

**Development of Quantum Mechanical Memory**

We optimized fabrication processes and established a measurement environment aimed at improving the coherence time of the mechanical memory and the conversion efficiency of the quantum transducer. For the evaluation of optomechanical devices at $^3$He temperatures, a helium cryostat was installed (see Photo 1).

Photo 1. Installed $^3$He Refrigerator

In addition, to reduce internal losses in rib-type optical waveguides for quantum transducers, we introduced a chemical mechanical polishing (CMP) process, which successfully decreased surface roughness (see Photo 2).

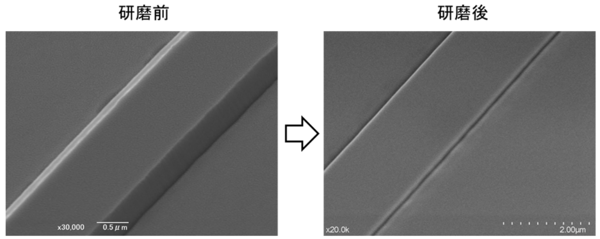



Photo 2. Surface-Polished Optical Waveguide

Furthermore, in our efforts to improve the coherence time of the mechanical memory, we developed a mechanical memory on a piezoelectric thin film that can be fabricated on the same chip as the photonic devices.

### 3. Future plans

We aim to advance toward quantum repeater technologies, including the demonstration of entanglement between quantum memories. Furthermore, through the development of quantum mechanical memories and quantum transducers, we will work toward interfacing superconducting quantum computers with quantum communication networks.



Japan Science and Technology Agency

R&D Item

# 4. Distributed Quantum Applications Enabled by Distributed Environments for Quantum Information

## Progress until FY2024

### 1. Outline of the project

This year we extended a quantumness-evaluation theory—originally created for a single-node, single-link setup—to a two-node quantum network, deriving comprehensive metrics that encompass each node's intrinsic quantumness and the Bell-state fidelity needed for remote-CNOT execution. We also devised a framework that systematizes the information and procedures required to prepare and run quantum-internet applications, adding new rules that embed application-specific data into RuleSet-based protocols and enabling automatic conversion into an intermediate representation (IR) for formal verification, thereby linking protocols seamlessly from the application layer down to the physical layer. In addition, we proposed a quasiprobability-based method that lowers sampling costs when generating entanglement between distant nodes, and, looking toward integration with quantum computing, theoretically identified useful applications for quantum-sensor networks and NISQ devices—for example, an entanglement-enhanced binary-classification scheme in an optical quantum-sensor network inspired by the Deutsch–Jozsa algorithm.

### 2. Outcome so far

(1) Developed theory that evaluates the quantumness required for remote-CNOT implementation in a system of two single-qubit processors connected by one link, thereby providing a method to assess both individual-node quantumness and overall device quality in a two-node quantum network, including estimation of link Bell-state fidelity.

(2) Proposed a framework that clarifies inter-node communication steps for the preparation and execution phases of quantum-internet applications and introduces new rules embedding application-specific information into RuleSets; designed a function that converts this description into an IR suitable for protocol verification, achieving seamless connectivity across all network layers.

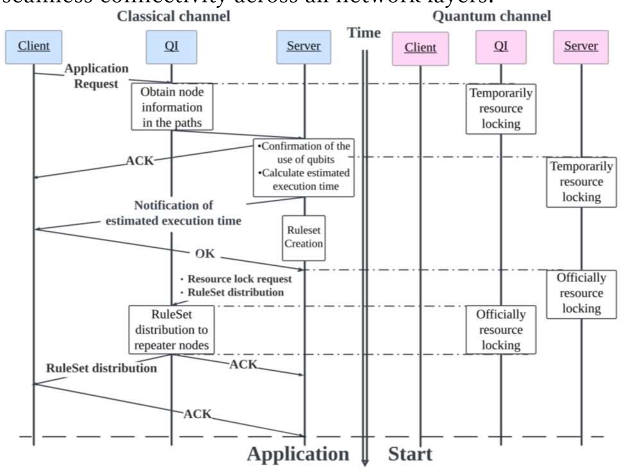



Fig. 1. Communication Procedure for Application Preparation.

(3) Improved the efficiency of distillation in distributed quantum computing by analyzing the dynamics of distributed quantum sensors and processors and applying a quasiprobability method to NISQ devices, thereby proposing a low-sampling-cost way to generate entanglement between distant nodes at the expectation-value level.

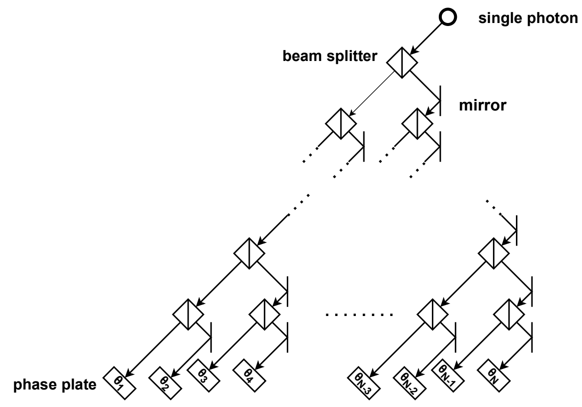



Fig. 2. Schematic of quantum sensing network

(4) Proposed a binary-classification method for optical quantum-sensor networks that uses entangled light to classify phase distributions, inspired by the Deutsch–Jozsa algorithm, demonstrating high-efficiency classification.

### 3. Future plans

Aiming to design algorithms and applications that maximize the performance of distributed quantum computation, we will, in the coming fiscal year—which marks a key milestone for our Moonshot goal—shift from design to operation in a platform-agnostic fashion. We intend to derive concrete cost metrics for distributed quantum computing and establish performance-assessment methods geared toward practical uses such as quantum sensing, thereby further deepening and expanding knowledge that supports real-world deployment of quantum information processing.

R&D Item

# 5. Testbed and Integrated Implementation for Integrating and Demonstrating Technologies

## Progress until FY2024

### 1. Outline of the project

This constructing testbed is a core system in this project and planned to be a public facility in the future for universities, national laboratories, and companies to test or validate hardware and software for quantum computer network. The testbed has two main functionalities to be established:

1. Scalability by integrating quantum optics and optical technologies
2. Actual distributed quantum computation by connecting multiple quantum computers

We design the testbed can connect arbitrary type of quantum computers, but first promising candidate is ion-trap quantum computer which can be connected by light directly.

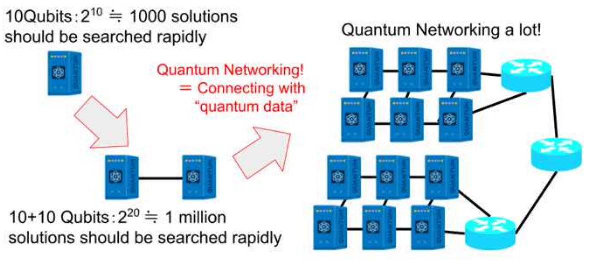



Fig 1. Scalable distributed quantum computer

### 2. Outcome so far

We launched from 2022, and grew up, then we have already integrated the basic optical technologies into our prototype system and we validate remote quantum entanglement between different quantum nodes principally by physical experiments.

Fig 2. Testbed overview in our laboratory.

We have justified the prototype system work well and, establish remote entanglement between selected two of three node. It means the system have functionality of switching or routing the nodes to be connected.

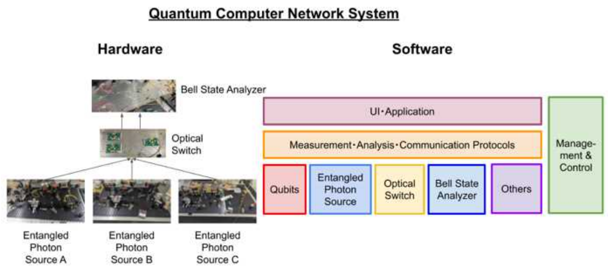



Fig 3. System architecture (left) three end nodes and 1 switch node hardware (right) software stack for control and operation

We are developing a photonically interconnectable trapped-ion quantum node. We recently succeeded in trapping and laser cooling of strontium atomic ions in a vacuum, as shown in Fig. 4.

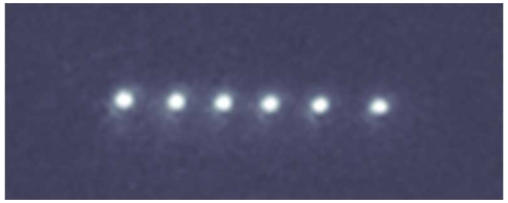


Fig 4. Fluorescence image of trapped strontium atoms

### 3. Future plans

We are planning to connect actual quantum computers, and realize fault-tolerant distributed quantum computation. To achieve this purpose, we develop high scalable network control and management system and communication protocol.

Furthermore, we will expand our concept of quantum network system to work in arbitrary type of quantum computers.